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Stability Thresholds and Performance Standards for Flexible Lining Materials in Channel and Slope Restoration Applications

by Sarah J. Miller[1], J. Craig Fischenich[1], and Christopher I. Thornton[2]

SUMMARY: Selecting the right channel and bank stabilization materials for channel restoration is critical, but is complicated by the limited availability of comprehensive performance criteria, an increasing number of new materials, and limited information regarding installation methods. Performance criteria for channel stabilization materials have traditionally focused on hydraulic parameters such as shear stress and flow velocity, but field performance of these materials is also dependent on non-hydraulic factors. Material selection, design, construction, and installation procedures are all critical to performance and project success. This technical note is intended to supplement recommendations provided in ERDC TN-EMRRP-SR-29, "Stability Thresholds for Stream Restoration Materials" (Fischenich 2001), which focused on hydraulic performance data for a variety of materials. This supplement focuses on flexible channel lining materials. An overview of selected design and installation criteria is provided, including critical materials properties, regional or climatic conditions, ecological considerations, and specific project applications. Project failure mechanisms are also discussed. Recommendations for product selection and field installation monitoring are summarized.

INTRODUCTION: Conventional river engineering and stream restoration projects share several common elements in design; one of these is determining methods and materials to stabilize channel boundaries (bed and banks) or slopes. For the purposes of this document, channel banks can be considered slopes or side slopes, though differences in selected restoration methods and materials for any given sloped area depend most on the combination of slope properties and characteristics of destabilizing factors. The number and combinations of materials and products that may be used in stabilization and restoration are as numerous as the possible combinations of slope and stress characteristics. The U.S. Environmental Protection Agency (USEPA), the American Society for Testing and Materials (ASTM), and the Erosion Control Technology Council (ECTC) have developed and continue to expand on industry-specific erosion control terms, definitions, and performance standards for these materials. Federal USEPA, ASTM, and ECTC naming and definition conventions are followed in this technical note, with exceptions noted where select industry terms are used (Table 1).

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Table 1. Terms and definitions for erosion control products in this technical note.

Full Term	Abbreviation	Brief Overview	Source
Erosion control blanket or temporary RECP	ECB	Temporary erosion control lining material, produced in rolls, bio-degradable	USEPA, ASTM, ECTC
Rolled erosion control product	RECP	Erosion control product produced in a roll, natural or synthetic, degradable or non-degradable, short- or long-term	USEPA, ASTM, ECTC
Turf reinforcement mat	TRM	A type of RECP, made of synthetic non-degradable (permanent) materials	USEPA, ASTM, ECTC
Ordinary TRM	-	Sub-category of TRM, up to 5-year functional longevity and minimum (MARV) 125 x 125 lb/ft^2 (6 x 6 kN/m^2) tensile strength[1]	Select industry term
Advanced TRM	-	Sub-category of TRM, up to 25-year functional longevity and minimum (MARV) 1,500 x 1,500 lbs/ft^2 (71.8 x 71.8 kN/m^2) tensile strength*	Select industry term
High performance turf reinforcement mat	HPTRM	A type of RECP, 100% synthetic non-degradable materials, designed for longer project life in more extreme field conditions (up to 50-year functional longevity) and minimum (MARV) 3,000 x 3,000 lb/ft^2 (143.6 x 143.6 kN/m^2) tensile strength[1]	EPA, Select industry term
Anchored reinforced vegetation system	ARVS	Installation using HPTRM with specialized tie-down anchors, usually for erosion control and slope stabilization	Select industry term
Vegetated reinforced soil slope	VRSS	A bioengineered system of geotextile-wrapped, vegetated soil lifts	USACE, relatively common industry term
Articulated concrete block	ACB	Hard armor revetment using interlocking concrete blocks of specialized shape	ASTM, common industry term
Bioengineering	-	Structural applications using vegetation- seed, plants, live cuttings and/or wood	NRCS, common industry term
Ultra short-term RECP	-	3-month functional longevity	ECTC, ASTM
Short-term RECP	-	12-month functional longevity	ECTC
Extended-term RECP	-	24-month functional longevity	ECTC
Long-term RECP	-	36-month functional longevity	ECTC
Permanent	-	Applies to RECPs classified as TRMs – composed of non-degradable materials, functional longevity 5 to 50 years	USEPA, ECTC, ASTM

[1] Tensile strength values represent minimum permissible for TRM category, reported for both machined direction (in the direction of manufacture or roll) and cross-machined direction (across the width of roll). The material must meet the minimum for both directions.

As part of a restoration project, channel banks and slopes are frequently lined, armored, or stabilized using materials and techniques that have evolved rapidly over the last several decades and are described by an entirely new, and not always consistent, industry lexicon. Functionally speaking, channel lining materials can be initially categorized as follows: hard or heavy-duty armoring (e.g., riprap, concrete), soft or light armoring (e.g., erosion control blankets, ECBs, an early type of so-called rolled erosion control product, reinforced vegetation), natural vegetative or soil bioengineering techniques (with or without use of inert materials), or some combination of revetment materials as part of a slope stabilization system (Di Pietro and Brunet 2002). The primary purpose of bank armoring is to prevent undesirable erosion resulting from hydraulic or surficial geotechnical forces expected at some stage during project life. Restoration designers must ensure therefore that materials placed within the channel or on the banks will be stable for the full range of conditions expected during the design life of the project.

This technical note discusses three general categories of materials for addressing erosion control, similar to the functional definition above and consistent with EPA designation (Figure 1): (1) Natural vegetation (this category includes temporary or degradable rolled erosion control products, RECPs), (2) Reinforced vegetation (two sub-categories, turf reinforcement mats, TRM), and (3) Hard armor techniques (e.g., concrete, riprap). Combinations of these categories can be considered slope stabilization systems. Some of these combinations are widely used (placing fabric behind riprap, for example), while others constitute proprietary combinations of materials and methods (e.g., anchored reinforced vegetation systems, ARVS, see Table 1). To the extent that these systems have been used enough to have a performance track record of import to the design engineer, they have been included herein.

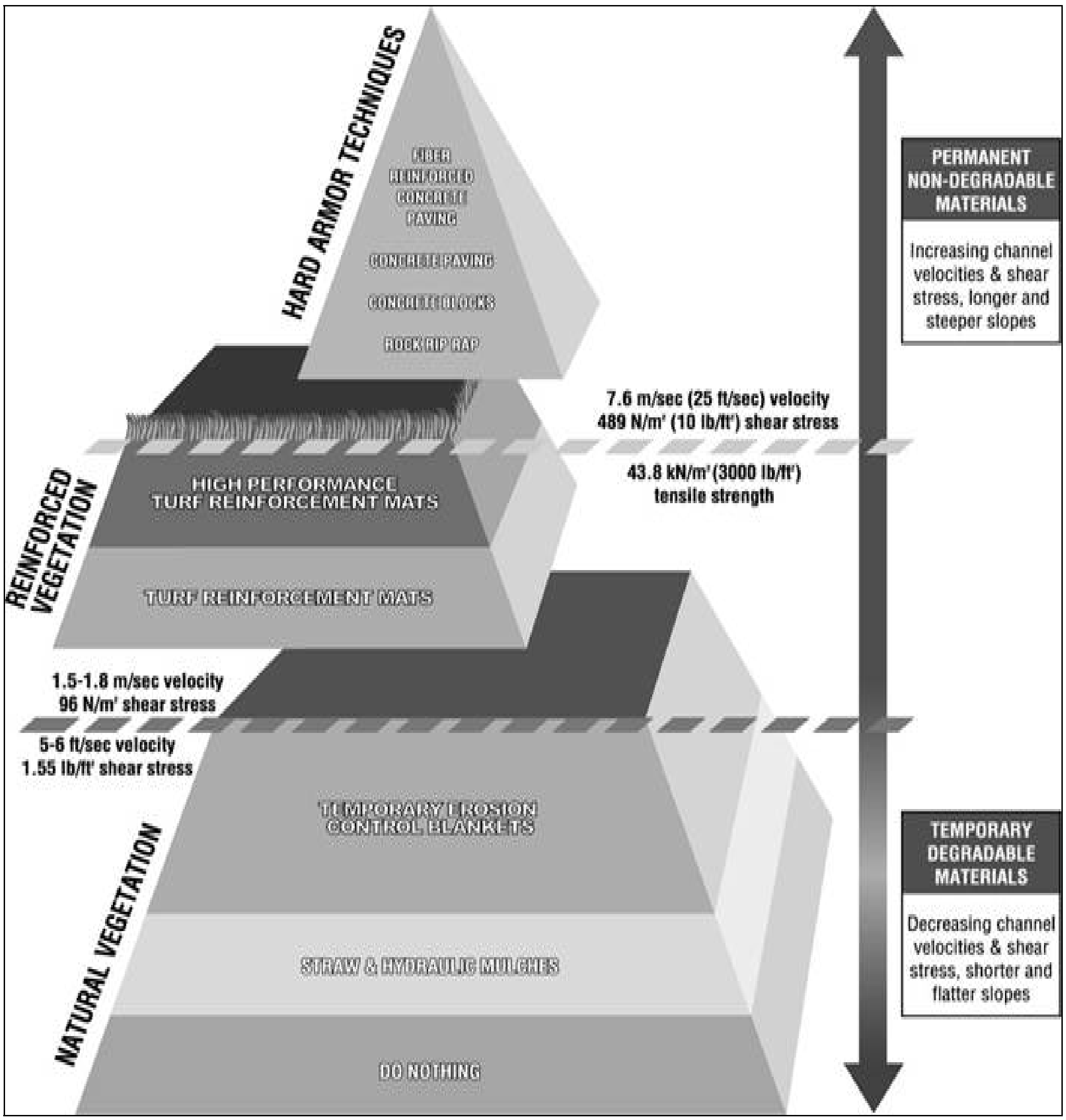


Figure 1. Erosion control techniques, Source: Synthetic Industries, 1998 (USEPA 1999b).

Selecting the right materials is critical to both short-term and long-term stabilization success, as well as to satisfying other project goals such as habitat provision, protection of riparian processes, lowering operation and maintenance costs, extending project life, or addressing aesthetic concerns. Issues that pose an industry challenge for effective application of the use of some erosion control materials, particularly RECPs, include limited availability of comprehensive performance criteria and data, the constant introduction and redefining of new categories and types of products, and a general lack of standard installation guidelines. Performance criteria for channel stabilization materials have traditionally focused on hydraulic parameters such as shear stress and flow velocity (typically downstream or down-slope), but field performance for these materials is also highly dependent on non-hydraulic factors (e.g., UV resistance, tensile strength). All of these performance parameters must be considered to ensure project success.

REGULATIONS AND MATERIALS DEVELOPMENT BACKGROUND: The regulation entitled "National Pollution Discharge Elimination System (NPDES) - Regulations for Revision of the Water Pollution Control Program Addressing Storm Water Discharges" was published by the USEPA on December 8, 1999 (64 FR 68722). This regulation, known as Phase II of the storm water program, expanded on the 1990 NPDES, which responded to the following statistics:

- Erosion-related pollutants cost the United States up to $13 billion annually (in 1999).
- Every year, the United States spent over $1 billion removing sediment from harbors and waterways.
- Annual water storage replacement costs from sediment ranged from $2 to $6 billion.

Due in large part to continuing updates to the USEPA Clean Water Act (CWA) and the NPDES Phase II permit coverage, the erosion and sediment control industry has continued to develop new products and procedures to address these issues (Theisen 2005, Khanna 2005, Lancaster and Austin 2003). The USEPA has designated turf reinforcement mats (TRMs), vegetated swales, and vegetated covers as best management practices (BMPs) for stabilizing disturbed soil for sediment control, setting the stage for a continuing expansion of the variety and utility of these products, the use of which has more than tripled since 1996 (Theisen 2005, Li and Khanna 2008).

An effective way to prevent erosion is to stabilize disturbed land through the addition of vegetation. Vegetation can be used effectively on slopes or in swales/channels with conditions conducive to the growth and health of the vegetation, and where the hydraulic stresses do not already exceed stability limits for the vegetation. Vegetation can reduce erosion potential by armoring the underlying soil, increasing infiltration, trapping sediment, and increasing the soil strength due to root penetration. However, the ability of vegetation to perform these functions is not constant, and varies with the type, condition, and maturity of the vegetation, especially as vegetation is becoming established. In general, any RECP can facilitate vegetation establishment and provide initial stabilization functions, making combined RECP/vegetation systems desirable (Khanna 2005). However, not all RECPs are created equally, and various sectors within the industry have divided and sub-divided RECPs to differentiate temporary or degradable from so-called permanent products. For example, ASTM defines categories of RECPs as temporary (includes ECBs) and so-called "permanent" (includes TRMs).

> <u>Erosion Control Blanket (ECB)</u> - in erosion control, n. - a temporary degradable Rolled Erosion Control Product (RECP) composed of processed natural or synthetic fibers, or a

combination thereof, mechanically, structurally or chemically bound together to form a continuous matrix.

Turf Reinforcement Mat (TRM) - in erosion control, n. - a non-degradable geosynthetic…processed into a matrix sufficient to increase the stability threshold of otherwise unreinforced established vegetation. Products in this category may incorporate ancillary degradable components to enhance the germination and establishment of vegetation.

Unlike temporary or degradable ECBs, TRMs can greatly increase hydraulic resistance limits of even fully established natural vegetation by reinforcing the vegetative root structure and providing greater stability during and beyond vegetation establishment through the design lifespan of the project (Figure 1, USEPA (1999a)). Based on testing at Colorado State University Hydraulics Laboratory over the past 10 years, scientists have found that reinforced vegetative covers have successfully increased the instantaneous peak hydraulic resistance limits of natural vegetation by up to 20 ft/s (6.1 m/s) velocity and 14 lb/ft^2 (670 N/m^2) shear stress. This increase allows for the use of reinforced vegetative covers where design discharges exert velocities and/or shear stresses that exceed the resistance limits of mature natural vegetation alone, giving designers additional soft armor options for bank and slope stabilization. In some applications, reinforced vegetative covers can be used in lieu of rock riprap, concrete paving, or articulated block or gabions, providing new stabilization options in higher stress environments.

FLEXIBLE CHANNEL LINING STABILITY CONSIDERATIONS: Manufactured flexible degradable erosion control blankets (classified as temporary or short-term RECPs) have proven to be effective in reducing erosion by providing immediate erosion protection, bridging the gap between vegetation installation and full establishment (Mohseni et al. 2004). Degradable RECPs have been in use for at least 50 years, with relatively well-documented performance results in both field and laboratory conditions, though precise functional longevity remains difficult to predict due to the number of environmental factors that can shorten design life (Austin and Ward 1996, Theisen 2005, McCullah and Gray 2005, Sutherland 1998). Non-degradable or “permanent” RECPs, introduced in Europe in the 1970’s, continue to be refined and tested as newer generation TRMs are introduced (Theisen 1992, 2005). Several broad categories of permanent vegetated armoring system materials are commonly used for channel and slope stability applications. Additionally, permanent vegetated armoring systems are often used with other armoring products, such as hard armor or geogrid, etc., as part of the revetment system. Regardless of product type, a number of performance considerations influence the success or failure of a stabilization project throughout its design life.

Performance during four phases of product design life. Stabilization projects using vegetation with flexible channel lining materials can be considered to experience stages in performance, with function or capability often at its lowest immediately following installation when soil disturbance is greatest and any vegetative component is not yet established. The “final” established or settled condition prior to any degradation constitutes peak performance. Useful performance of geosynthetic products can be divided into four life stages:

1) Unvegetated or minimally vegetated (as-built or unvegetated HPTRM).
2) Partially vegetated (establishment phase).

3) Vegetated or performance phase to equilibrium.
4) Some degradation point followed by decay if equilibrium is not possible (Nelsen 2005).

Additionally, the rate at which installed geosynthetic product performance values (strength, flexibility, etc.) diminish over time varies greatly by material and manufacturer within the industry. The designer must account for both project-specific design life requirements and long-term product-specific performance values to adequately select the appropriate permanent vegetated armoring system. For example, many agencies use a benefit-cost ratio assuming a 50-year design life. Product design life and specific long-term product performance values of the selected permanent vegetated armoring system would factor into quantifying not only initial installation costs, but long-term maintenance and replacement costs as well.

Despite advances in materials and expanded application techniques, projects that include these materials are still subject to failure. While hydraulic flanking, overtopping, and undermining due to improperly installed or insufficient keyways are among the most common reasons for riprap failure (Lagasse et al. 2006), failure of permanent vegetated armoring systems are most likely to occur due to one or more of the following:

- Wrong product for appropriate application.
- Inadequate design criteria or assessment (hydraulic or non-hydraulic stresses).
- Improper installation.
- Poor maintenance.
- Faulty product (e.g., low-grade materials used during manufacture).

Hydraulic criteria (e.g., velocity and shear stress) are typically the only parameters addressed during the design process. Other environmental stressors are important as well, and failure to take into account all project-specific performance factors including slope stability, debris loads, maintenance or recreational traffic (e.g., all-terrain vehicles, mowers or equestrian traffic), high ultra-violet (UV) light exposures, etc., can lead to product and project failure (Figures 2 and 3).

The most common failure mechanism of permanent vegetated armoring systems is a lack of UV stability, often leading to insufficient tensile strength (Koerner et al. 2005, Li and Khanna 2008). Both of these failure mechanisms are readily preventable, primarily through consideration of local conditions, vegetation requirements, and characteristics and type of

Figure 2. Ultra-violet light degradation of an under-vegetated turf reinforcement mat.

Figure 3. Insufficient tensile strength and poor seams can lead to mower damage.

RECP material employed. Projects that fail to consider UV stability and tensile strength will have a higher probability of failure.

HYDRAULIC DESIGN CONSIDERATIONS: Erosion control is sometimes required in situations where the hydraulic or geotechnical forces exceed the level of protection afforded by vegetation alone, or some additional protection is required for the period between installation and full establishment of mature vegetative cover. In these circumstances, a combination of vegetation and other inert materials may meet the project objectives. The design must take into account the combined performance of both the living and inert components.

Restoration designers planning to use reinforced vegetation must consider many of the same criteria as unreinforced vegetative cover or hard armor stabilization materials without vegetation. Following initial investigation and characterization of geotechnical or slope stability parameters that necessitate revetment (not covered in this technical note), hydraulic conditions are among the more important elements to consider in channel and slope design. Discussion of hydraulic considerations below applies primarily to channel applications. In hillslope settings, additional factors are used to determine limiting hydraulic conditions, such as precipitation characteristics, runoff, and groundwater fluctuations. Though not covered in detail in this technical note, the restoration designer must account for such hydraulic elements as the range of pool elevation (lake or reservoir), ship wakes, storm or wind-driven waves, tidal fluctuations, and runup and overtopping or overwash conditions (Jones and Broker 2005).

Design discharge. Quantifying the magnitude, frequency, and duration of expected discharge events is important for determining limiting hydraulic conditions that will affect stability and longevity of constructed projects and installed materials. In channel settings, design discharge can be determined using one or more of a number of generally accepted methods. These may include the rational method, runoff curve number method, hydraulic modeling (e.g., HEC-15, HEC-RAS), or evaluation of historical gage records or flood frequency distributions. The materials used to stabilize channels or banks should be capable of withstanding the full range of discharges (and associated conditions) to which they will be subjected. As a practical matter, it is not possible to assess every possible discharge, so channel restoration designers generally consider three categories of flow conditions: limiting low flows for aquatic habitat design (e.g., summer base flow), high flows that begin to impact channel and bank stability and sediment transport for selection of structural methods (e.g., bankfull or dominant discharge), and extreme events (e.g., 50- or 100-year flood) to assess flood surface elevations for project design life or regulatory concerns (Fischenich and Allen 2000).

Flow velocity. Most materials typically used in channel stabilization applications have been studied empirically or modeled to determine the maximum channel-averaged flow velocity the material can withstand without eroding (Fischenich 2001, Table 2). Maximum permissible velocity, also referred to as critical or limiting velocity, defines the threshold condition for the material or project above which bed or bank materials begin to erode. Velocity must be determined for the range of expected discharge to determine the maximum expected velocity for site conditions. Velocity is then compared with the maximum velocity that various channel lining materials can withstand. This process can be referred to as stability threshold analysis (Fischenich and Allen 2000, Frothingham 2008).

Table 2. Strength retention per ASTM standards with corresponding design life in years.

Tensile Strength Retained	Estimated Product Design Life	Specified Test Method
90% @ 500 hours	Up to 5 years	ASTM D 4355
90% @ 1,000 hours	Up to 10 years	ASTM D 4355
90% @ 2,500 hours	Up to 25 years	ASTM D 4355
90% @ 5,000 hours	Up to 50 years	ASTM D 4355

Directly measured velocity data are virtually never available for the critical discharge, so they must be estimated or calculated. One common method for estimating average cross-section velocity relies on Manning's equation, solving for the mean channel velocity, V, in feet per second (ft/s or fps),

$$V = (1.486/n)R^{2/3}S_f^{1/2} \quad (1)$$

where

n = Manning's roughness coefficient (dimensionless)
R = hydraulic radius in feet (ft) or meters (m)
S_f = friction slope (ft/ft or m/m)

For SI units, use 1.0 instead of 1.486 in Equation 1. Under steady uniform flow conditions, friction slope may be assumed equal to bed slope (S_0), and R may be assumed equal to average depth, particularly for channels that are very wide in comparison to depth and more closely represent uniform flow assumptions. For narrow and deep channels, calculate R = A/P, where A is cross-sectional area in square feet or square meters and P is the wetted perimeter in feet or meters.

Note that uniform flow conditions are rare in natural settings, so results will be approximate. Additionally, Equation 1 yields an average channel velocity; velocities can vary considerably within a cross section or reach, particularly throughout channel bends, and especially along channel banks or side slopes. Estimating characteristic side slope velocity for curved channels is recommended to best estimate permissible velocities on channel banks, which can be considerably higher than channel average. EM 1110-2-1601 (USACE 1994) presents a straightforward method wherein a hydraulic model-derived curve relates the ratio of design radius of curvature to top water width against the ratio of side slope velocity to depth-averaged channel velocity. Ratio of radius of curvature to top water width is calculated and compared to the curve to get the appropriate ratio of slope velocity to average velocity; then average velocity is used to calculate side slope velocity.

If critical hydraulic stresses are anticipated prior to the full establishment of vegetation, choice of *n* value must reflect the unvegetated condition as well as the final or established project design to enable appropriate selection of stabilization materials that can withstand the full range of hydraulic conditions at every stage of project design life. McKay and Fischenich (2011) provide detailed description and discussion of channel boundary roughness and also present a useful tool for estimating roughness in channel settings.

Shear stress. Maximum permissible velocity is a spatial and temporal average for the cross section of interest. Cross sections of very different shapes may produce the same average velocity,

though forces exerted at the channel boundary (bed and banks), and how those forces affect boundary materials, may differ markedly (Theisen 1992). For that reason, shear stress is a parameter that better represents hydraulic forces and therefore is more useful in calculating threshold conditions and determining appropriate channel lining materials than velocity alone. Stability threshold analysis for bank stabilization most often considers permissible velocity and shear stress thresholds together (Frothingham 2008).

Channel boundary shear stress (also called tractive force or entrainment force) represents the combination of drag and lift forces acting on channel boundary materials (Dingman 1984). Boundary shear stress, or fluid force per unit area in the direction of flow, increases as flow depth and water surface slope increase. Mean channel shear stress τ_0 in pounds per square foot (lb/ft^2) or Newtons per square meter (N/m^2) is most commonly calculated as a function of the properties of flowing water using:

$$\tau_0 = \gamma R S_0 \tag{2}$$

where

γ = specific weight of water, in pounds per cubic foot (lb/ft^3) or kilograms per cubic meter (kg/m^3)

Equation 2 represents a reachwise average estimate of shear stress assuming uniform flow conditions, though it is commonly used in natural settings. Restoration designers should be aware that the greater the deviation in conditions from the assumptions of steady, uniform flow, the less accurate this estimate of shear stress will be. As for Equation 1, R can be approximated by average depth (d) in most natural channels.

The relationship between permissible shear stress and permissible velocity for a lining can be found by considering the continuity equation solving for discharge, Q in cubic feet per second (ft^3/s or cfs) or cubic meters per second (m^3/s or cms):

$$Q = VA \tag{3}$$

where

V = flow velocity, m/s (ft/s)
A = area of flow, m (ft^2)

By substituting Equation 2 into Equation 1:

$$Vp = \frac{a}{n\sqrt{\gamma d}} R^{1/6} \tau_p^{1/2} \tag{4}$$

where

Vp= permissible velocity, m/s (ft/s)
τp = permissible shear stress, N/m2 (lb/ft^2)
α = unit conversion constant, 1.0 (SI), 1.49 (CU)

If the slope in the direction of flow is greater than 20%, a closer approximation of the bed shear stress may be calculated using a control volume and conservation of momentum. This approach results in

$$\tau_0 = \gamma \cdot \frac{(D_1 + D_2)}{2} \sin\theta + \frac{1}{L}\left[\frac{\gamma}{2}\left(D_1^2 - D_2^2\right)\cos\theta - \left(\frac{1}{D_2} - \frac{1}{D_1}\right)\right] \tag{5}$$

where

D1, *D2* = upstream and downstream depths, respectively (ft or m)
θ = channel bed slope (degrees)
L = length of control volume (ft or m)

D_1 is determined at the upstream end using Manning's equation and the design discharge.

Both velocity and shear stress have unequal distribution within a channel cross section (Figure 4, Lagasse et al. 2006). Instantaneous or at-a-station values can be two or three times the cross-sectional average value, and conditions in flumes in which many studies were done differ markedly from field conditions. However, reported values represent a fair first-cut approximation for the restoration designer.

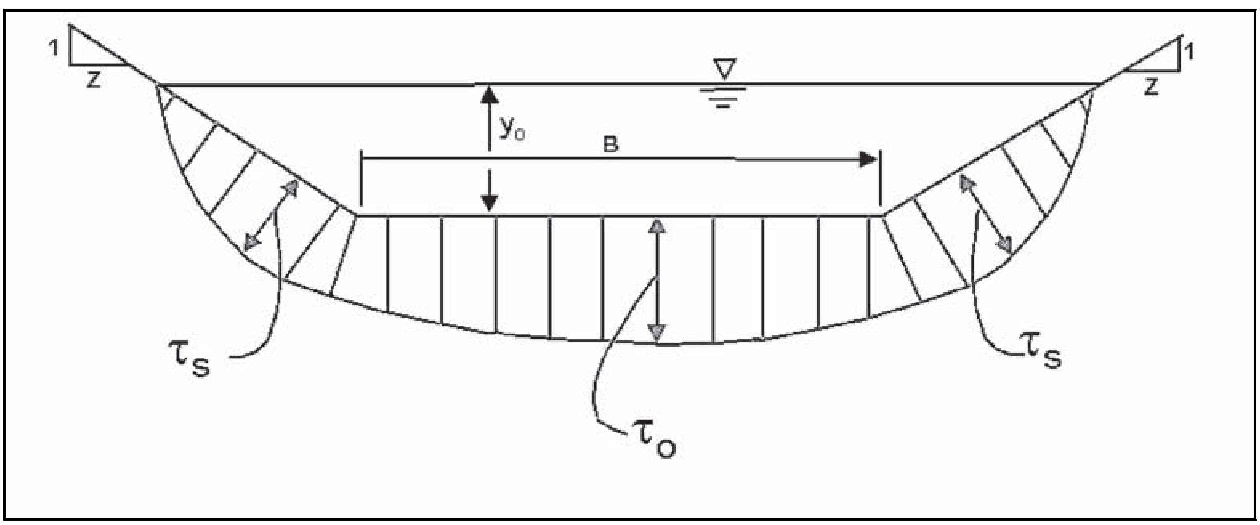


Figure 4. Shear stress distribution in a trapezoidal channel. Source: Lagasse et al. (2006), modified from Chen and Cotton (1988).

Shear stress is not constant in a reach, but varies with depth and channel geometry (Pitt et al. 2007). Where some estimate of local maximum shear stress is desired, this may be calculated

using an at-a-station depth in place of hydraulic radius in Equation 2 (Pitt et al. 2007). Alternatively, for straight channels, maximum average shear stress can be approximated by:

$$\tau_{\max} = 1.5\,\tau \tag{6}$$

and for sinuous channels, maximum shear stress should be determined as a function of planform characteristics:

$$\tau_{\max} = 2.65\,\tau\left(\frac{R_c}{W}\right)^{-0.5} \tag{7}$$

where R_c is radius of curvature in feet or meters and W is channel surface width in feet or meters (Chang 1988, Fischenich 2001). Fischenich (2001) notes turbulence may add 10–20 %, so an adjustment factor of 1.15 is typically applied to account for instantaneous maxima.

The zone of localized increase in shear stress is assumed to begin along the outside bank just downstream of the bend, extending some length related to hydraulic radius and channel roughness (Pitt et al. 2007). Additional or stronger lining materials may be required in this length of channel, L_p, which can be estimated according to Pitt et al. (2007) by:

$$L_p = \left(0.604R^{1.17}\right)/\,n \tag{8}$$

Flow duration. A typical hydraulic design criterion for TRM Systems can be based on a duration discharge hydrograph using a specific or representative flood event to show elapsed time for flow above a selected rate or percentage of peak flow (Figure 5). Any flow rate can be chosen as the benchmark flow, based on threshold value, recurrence interval, or other factor, the point being that it is not only instantaneous peak discharge that impacts stability, but a flow rate over time. Flow duration of interest in this example is from 90% of instantaneous peak discharge on the rising limb to 90% of

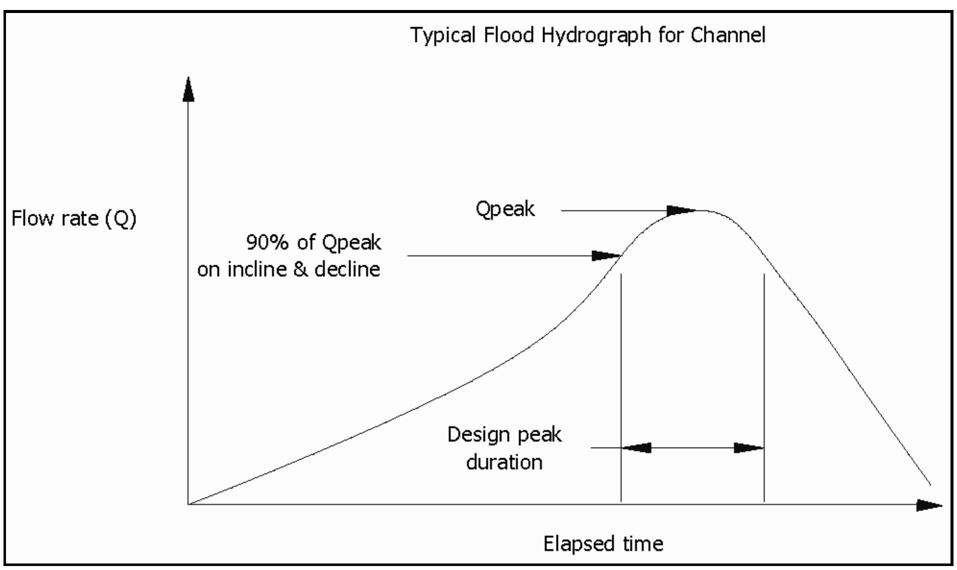


Figure 5. Representative flood event hydrograph for a small basin showing peak discharge (Qpeak) and duration of flow exceeding 90% of Qpeak.

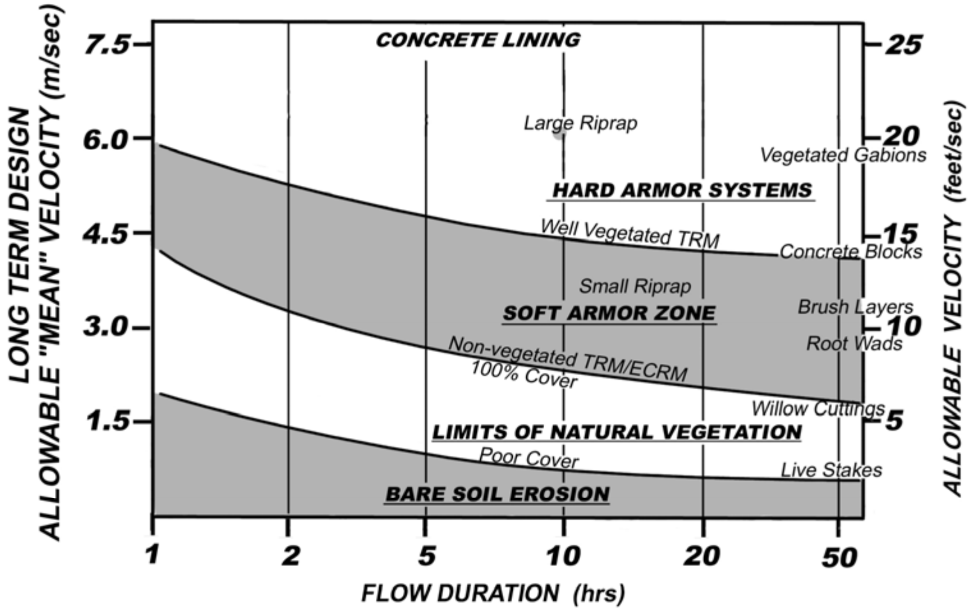
peak discharge on the declining limb, not necessarily the duration of the entire storm event. Duration of any greater-than-threshold flows can impact stability and erosion of boundary materials. A typical 24-hr event in a small watershed for stormwater management might exhibit 20- to 30-minute duration of greater than 90% of peak discharge. Most manufacturer-reported values for maximum velocity or shear stress are based on similar short duration testing. However, if threshold flow rate is expected to occur for several hours or days, as in continuous flow settings such as reservoir spillways, longer duration testing may not be readily available for the complete range of materials, though specific manufacturers may be able to provide their recommendations for particular materials. Much of this information is proprietary, but inquiry is worthwhile if a specific lining material is desired, or if longer flow durations are expected.

Though many manufacturer-reported values for maximum velocity or shear stress are based on short duration testing, the importance of flow duration is becoming more widely recognized and researched (Theisen 1992, Nelsen 2005, Hoitsma and Payson 1998). Longer duration flows – hours to days – more closely represent field conditions. Erosive properties of soils change with saturation, vegetation becomes stressed or damaged, and properties of some lining materials change with long periods of inundation or hydraulic stress (Theisen 2005, Nelsen 2005). The result is that maximum reported shear stress and velocity may overestimate actual field performance of the full range of channel lining materials in the event of longer duration flows (Figure 6). Materials represented in Figure 6 can withstand between 1.5 and 3 times the velocity at 1 hr as at 50 hr flow duration. While this is a very rough rule of thumb, a minimum factor of 1.3 should be applied to manufacturer-published permissible velocity and shear stress results to account for any expected flow duration-related decreases in materials tolerances.

NON-HYDRAULIC DESIGN CONSIDERATIONS: The long-term performance of TRMs has traditionally been evaluated using hydraulic testing performance within controlled flume environments, or laboratory testing of specific parameters, usually conforming to ASTM or other industry standard. In recent years additional important design factors have been identified, from damages due to livestock grazing or insect infestation to drainage problems or soil conditions resulting in poor vegetative establishment (Mohseni et al. 2004). Specific field application studies have more recently been used to test for both individual and aggregate effects of environmental stresses over time (Li and Khanna 2008, Jeon et al 2006, Khanna 2005). As noted above, UV exposure, especially when combined with high or highly variable temperature and moisture, causes the greatest measurable degradation in polymers (Lodi et al. 2008, see Figure 2).

Khanna (2005) and Li and Khanna (2008) describe six broad categories of stressors or potential damages to RECPs that can cause decrease in performance, considered as a function of specific properties of these lining materials.

1. Environmental stress – tensile stresses that exceed the mechanical strength of the material accelerated by other stresses in the exposure environment.
2. Mechanical damage – localized damage due to externally applied loads such as debris or machinery, often during installation (Jeon et al. 2006) but also due to operation and maintenance activities (Figures 3 and 7) or hoofed/burrowing animals.



NOTES:

1. ***Hard Armor -*** *includes Concrete, Riprap, Gabions, Concrete Blocks, etc.*
2. ***Soft Armor -*** *includes Turf Reinforcement Mats (**TRM**), Erosion Control Revegetation Mats (**ECRM**), Vegetated Geocells, and many Biotechnical Treatments.*
3. *Available data shows considerable variability in limit velocities.*

Adapted from Thiesen (1992)
Used with permission of Synthetic Industries, Inc.; Fischenich and Allen (2000); McCullah and Gray (2005) (NCHRP 544)

Figure 6. Allowable velocities and flow duration for various erosion and bank protection measures.

Figure 7. Levee project – construction traffic on permanent vegetated armoring system.

3. Oxidation – due to exposure to air and water, a chemical reaction with a specific chemical group in a constituent polymer that leads to damage at a molecular level and changes in physical properties. Other chemical stresses can include acidity, corrosives, salinity, ozone and other air pollutants (Lodi et al. 2008).
4. Photo degradation – change in chemical structure due to exposure to UV wavelengths of sunlight, most often occurring during installation, prior to full vegetation establishment or inadequate vegetation establishment and coverage over time.
5. Temperature instability – changes in appearance, weight, dimension or other properties as a result of low, high, or cyclic temperature exposure.
6. Thermal degradation – exposure to heat can alter the chemical structure, which results in changes in physical properties.

As TRM or other materials are degrading, the vegetative component of a project is simultaneously becoming established, presumably leading to an overlap in effectiveness of each component (Figure 8). This produces an optimization exercise for the designer to determine the minimum combined materials strength of the project required to withstand expected conditions. For example, for a selected project, full vegetation doubles permissible shear stress of an unvegetated TRM but takes 5 years to establish, and the TRM is expected to lose a third of its tensile strength during that time. The weakest point in this design timeline – where vegetation is only partially established and TRM is already partially degraded –should constitute the maximum performance to assume in project design to ensure the site is never under-protected. The engineer must carefully evaluate published performance data for specific materials with anticipated degradation, consider specific performance added by vegetative components, and apply a factor of safety in choosing materials that may provide enough strength initially to bridge the gap.

RELEVANT MATERIAL PROPERTIES INFLUENCING MATERIALS PERFORMANCE: A combination of stresses exerted as a result of specific field conditions combine with materials composition and configuration to determine project performance. The three primary matrix configurations within the TRM industry include stitch-bonded, fused, and woven products. Each type of matrix configuration impacts long-term material performance properties and ultimately project success.

Equally important to product and project performance are the specific components that comprise a given TRM product. In the “non-degradable geosynthetic” category, TRM products consist primarily of nylon, polypropylene, polyethylene, polyester, and sometimes include bio-degradable components. Performance of different synthetic components can vary greatly when exposed to variations or extremes in such environmental conditions as humidity/moisture, UV light, pH level, temperature, etc. Specific advantages and disadvantages of the product(s) being considered in design of a stabilization project depend on properties of product components, and the product as a whole. For example, TRMs that contain biodegradable (temporary) components will perform very differently before and after the temporary components are gone. Polyester can be significantly affected by moisture and can be degraded over a wide range of pH levels. Nylon, a tough, translucent, crystalline material used primarily as a fiber polymer, can be significantly affected by the presence of moisture because it absorbs moisture and loses strength rapidly as humidity and temperature increase.

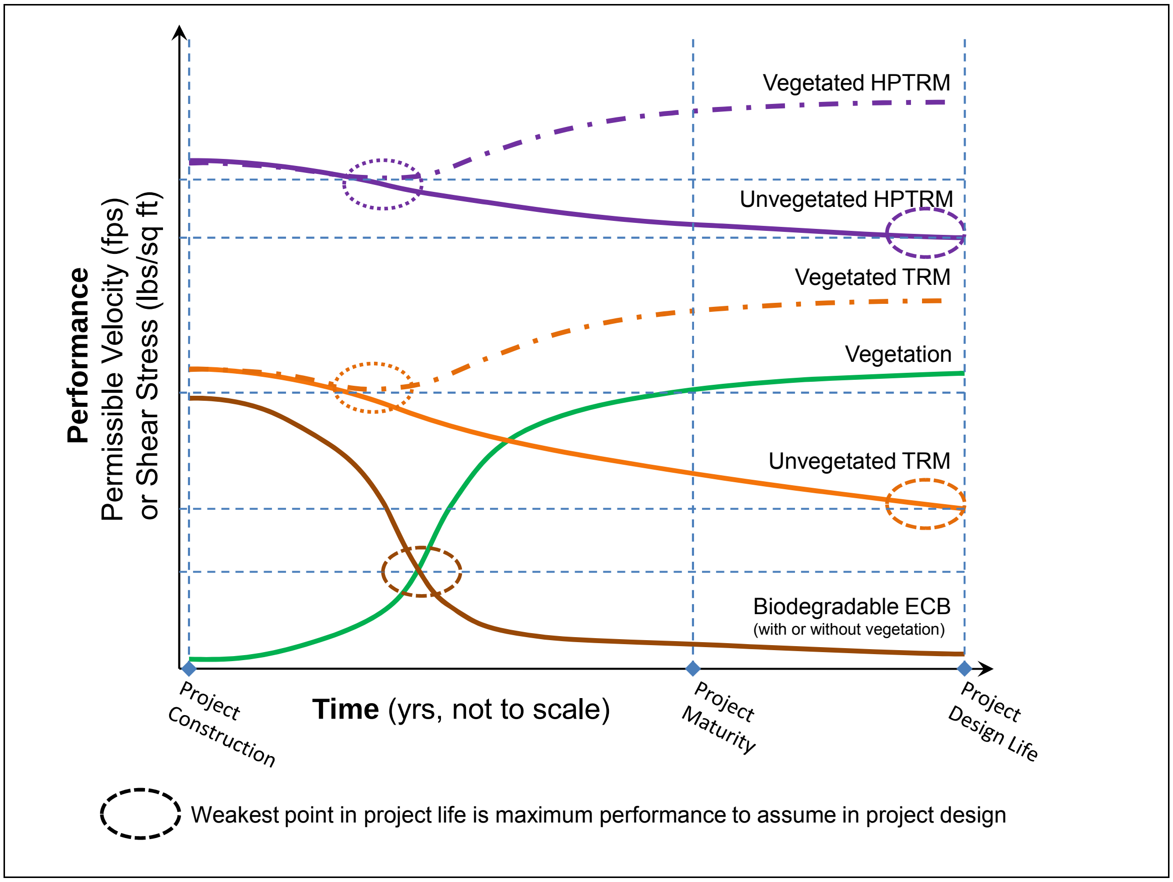


Figure 8. Conceptual performance effectiveness curves for vegetation and TRM over time.

Material property test results published by RECP and TRM manufacturers provide useful information on these types of performance factors for designers. Many of these tests have standardized methods, though most testing focuses on a single property at a time under controlled laboratory conditions and with new, unused material samples. To ensure quality control and applicability of published values, designers should verify that ASTM or other industry accepted testing standards are referenced and that these standards are appropriate to the application. For example, an ASTM test method specific to 6- by 6-in. (15.2- by 15.2-cm) TRM samples may provide different property test results than a similar method using 2- by 2-in. (5.1- by 5.1-cm) samples intended for the geotextile fabric industry. When considering results for an application, designers should refer to the *minimum average roll value* (MARV), defined as two standard deviations below the mean per ASTM D4439, to ensure the bulk of the material used consistently meets the minimum requirement for the project.

A number of ASTM tests are appropriate for TRM sample testing and are generally recognized as relevant to stability and performance in field applications. In a three-year TRM aging study of seven installed products, Li and Khanna (2008) measured the following common properties for used (applied in a field installation) and unused (preserved in original rolls) materials:

- mass per unit area (ASTM D5261)
- thickness (ASTM D5199)

- light penetration (ASTM D6567)
- swell (ASTM D1117)
- specific gravity (ASTM D792)
- resilience (ASTM D5199)
- stiffness (ASTM D1388)
- tensile strength (ASTM D5035-95, updated by D6818-02)
- water absorption (ASTM D1117)
- smolder resistance (ECTC-TASC 00197)

Mass per unit area, thickness, light penetration, swell, and specific gravity are examples of *manufacturing index properties* used for quality control to confirm consistency in the manufactured product. Manufacturing index properties may not have specific or direct correlation or relevancy to either design or long-term performance of the TRMs. *Performance properties* such as resilience, stiffness, tensile strength, water absorption, and smolder resistance more directly correlate to the long-term performance of an installation. Additional relevant performance properties not measured in the above studies include:

- UV resistance (ASTM D4355)
- flexibility (ASTM D6575)
- seedling emergence (ASTM D7322)

As noted above, the most common failure mechanisms for TRMs are directly or indirectly a function of a lack of UV stability or a lack of or reduction in tensile strength, so additional detailed discussion is provided below.

Manufacturers measure material properties in accordance with a Manufacturers' Quality Control (MQC) program to assure compliance with the requirements of the project material specification. TRMs are subject to sampling and testing to verify conformance with this project material specification in accordance with ASTM D4354. The manufacturer is required to keep a record of all MQC test results, and provide these on request. A manufacturer's certificate should state that the furnished TRM meets all MARV requirements of the specification as evaluated under the MQC program.

MQC Testing should be performed at a laboratory accredited by Geosynthetic Accreditation Institute – Laboratory Accreditation Program (GAI-LAP) at minimum frequencies required in ASTM D4354.

Of course not all of these properties may be important to every application, though a combination of environmental factors is most typically responsible for wear and tear or aging of materials even when used and installed as recommended. Reported values or limits for certain properties do not necessarily guarantee these values will persist when combined with other stressors in field applications, so these values should be used only as a guide to represent an initial condition (Li and Khanna 2008, Theisen 2005, Khanna 2005). Some methods are intended to mimic field conditions or to be conducted in the field (e.g., ASTM D5970 for actual field exposure to test UV impacts), though not all properties have field-standardized tests, and laboratory results are much more commonly reported (Koerner et al. 2005).

Flexibility. The flexibility of a TRM indicates its ability to maintain direct contact with the underlying soil subgrade. Flexibility is an important factor for vegetation establishment and prevention of erosion of surface fines. This property, along with stiffness and resilience, determines how well the TRM will stay in direct contact with the surface subgrade. Proper grading, preparation of the ground surface, appropriate soil fill materials, and planting methods are also important to maximize the potential for acceptable TRM product performance. However, even at sites where fine grading would be considered sufficient, unevenness and depressions will occur. If direct contact is not maintained between the surface subgrade and the TRM, problems may occur, including erosion beneath the mat and loss of potential vegetation where the separation occurs.

Flexibility is measured in inch-pounds; the greater the flexibility value, the greater the stiffness; the lower the flexibility value, the greater the flexibility. Published flexibility values range from less than 1 in.-lb per ASTM D-6576 (very flexible) to over 20 in.-lb (rather rigid), though few manufacturers currently publish flexibility values. Greater flexibility (lower values, less than 2 in.-lb) is recommended for TRM applications, ensuring more consistent contact with inevitable variable topography of typical project sites. Low tensile strength TRMs will generally have the greatest flexibility. In contrast, high tensile strength TRMs tend to be more rigid. Independent of tensile strength, TRM products with fused joints, stitch-bonded products with different components, and products that attempt to artificially increase the tensile strength of the TRM by attaching a geogrid, tend to be more rigid products. Flexibility may be impacted by environmental changes, such as heat or moisture, causing stitch-bonded or composite TRM products to buckle or pucker as individual components respond differently. Woven TRMs tend to provide a combination of high tensile strength and greater flexibility (low flexibility values).

Some civil engineering applications (beyond the scope of this technical note) require the added structural integrity of a more rigid product; examples of such applications are road subgrade stabilization, construction of retaining walls, or construction in areas with particularly weak, less compacted soils. Typically much more aggressive and comprehensive grading accompanies use of rigid products, and the material may be buried to some depth. As for all products and applications, careful examination of reported property values for the composite products, as well as the individual componens, is important to ensure that the right product is used.

UV resistance. Turf reinforcement mat products must adequately perform under site-specific sunlight exposure. Even with excellent vegetation development potential, some degree of UV exposure of a TRM product should be assumed during construction, following flood events, prior to or in case of lack of vegetation establishment due to mortality or vehicular traffic, etc. According to industry standards, 90% tensile strength retention at 1,000 hr corresponds to up to a 10-year lifespan (considered a “permanent” product) though many projects are designed for 25 or 50 years (Table 2). For longer design life, products must meet more stringent performance criteria.

In multi-component TRMs such as layered, stitch-bonded products, UV resistance testing and reporting for each component are critical in order to preserve long-term design properties and sustained durability. Selective degradation of product stitching or netting could result in delamination and unraveling if an inadequately tested stitch-bonded product is used in an

inappropriate setting. Once a stitch-bonded product delaminates, isolated failures can become catastrophic over a relatively short time period.

Tensile strength. Tensile strength is the property that enables a material to hold its shape and resist cracking, tearing, or other structural failure when subject to hydraulic and non-hydraulic forces. High tensile strength may not be required to withstand wear from typical channel velocities and shear stresses, but high tensile strength TRMs may be required to adequately address other non-hydraulic high wear stresses expected in real-world applications. Field conditions that put additional stress on the material might include lengthy or steep slopes requiring materials to cover large areas or complex terrain, high traffic, and natural or engineered loadings such as equipment, debris, and ice. Some persistent environmental conditions can act on the material to reduce existing tensile strength, such as extreme UV exposure and chemical or thermal stresses. Initial installation may damage or reduce material strength through activities that may include deliberate puncturing at connections to soil or hard armor or making openings for vegetation. In settings with specific non-hydraulic stresses such as these, designers should choose a product that can withstand additional forces that might expedite weathering processes that result in reductions in tensile strength. For example, a stitch-bonded product may not be able to withstand cutting, tearing, or other breaks in the fabric as might be required to work around trees or other vegetation or to drive in earth anchors (Baker 2008). In contrast, a woven material can be cut to accommodate vegetation even in severe slope settings that require materials with significant tensile strength, without compromising the installation (Figure 9, Baker 2008).

Figure 9. Slope application, CA, showing TRM cut to accommodate existing trees. Additional information on this case study available in Baker (2008).

Within the industry, tensile strength values for permanent TRMs vary from about 100 to 4,000 lb/ft^2 (4.8 to 191.5 kN/m^2) between materials, and can vary between machined (parallel to the direction of manufacture or along the roll of material) and cross-machined (across the width of the roll) directions. Designers should always verify which direction published values represent, and ensure that the lower tensile strength is used to set the minimum strength for the material. In addition, all components of a TRM should be tested and reported, as properties of various combinations of materials will result in differing performance of the composite material. Standard recommendations can be made for various applications (FHWA FP-03 Section 713.18, ECTC 2008, Table 3 (U.S. Department of Transportation, Federal Highway Administration 2003)). To qualify for a particular TRM designation, a product must equal or exceed both the UV resistance and tensile strength specified values, with tensile strength exceeding minimum values for both machined and cross-machined directions.

Table 3. Summary of standard ultra-violet light resistance and tensile strength recommendations for product classes.

Product Class	UV-Resistance (Minimum Values)		Tensile Strength (Minimum Average Roll Values)	
--	Tensile Strength Retained	Test Method	Tensile Strength	Test Method
Ordinary TRM	90% at 500 hours	ASTM D 4355	125 x 125 lb/ft^2 [1] (6 x 6 kN/m^2)	ASTM D 6818
Advanced TRM	90% at 2,500 hours	ASTM D 4355	1,500 x 1,500 lbs/ft^2 (71.8 x 71.8 kN/m^2)	ASTM D 6818
High Performance TRM (HPTRM)	90% at 5,000 hours	ASTM D 4355	3,000 x 3,000 lbs/ft^2 (143.6 x 143.6 kN/m^2)	ASTM D 6818
Anchor Reinforced Vegetation System (ARVS)	90% at 5,000 hours	ASTM D 4355	3,000 x 3,000 lbs/ft^2 (143.6 x 143.6 kN/m^2)	ASTM D 6818

[1]TRM category 5a – per ECTC standards, this category includes 5b (150 x 150 lb/ft) and 5c (175 x 175 lb/ft).

ADDITIONAL DESIGN CONSIDERATIONS

Environmental impacts. Environmental concerns regarding the use of TRMs have included wildlife entrapment potential (specifically for threatened or endangered species or in sensitive habitats), the risk of entire sections of mats washing downstream, the use of non-biodegradable products (geosynthetics, plastics, rebar, metal anchors, etc.) in natural settings, and limited benefits to or degradation of natural habitat elements in stabilized areas.

Wildlife entrapment. Fixed mesh openings can pose a serious threat to wildlife by entanglement until vegetation establishment and adherence of the TRM to the soil surface (ECTC 2008). Stitch-bonded, geosynthetic extruded and fused TRMs typically have opening sizes ranging from10 to 100 mm^2 (0.4 to 4 in.), large enough to entrap a variety of small animals. In an article titled "Do Erosion Control and Snakes Mesh?" (Barton and Kinkead 2005), authors studied 19 snake trappings at 9 of 15 monitored sites, one 8-ft by 90-ft (2.4- by 27.4-m) roll per site, four months after installation. According to the authors, 14 trapped snakes observed died either from overheating, lacerations from the netting, or being unable to escape from predators, although exact cause of death could not be determined for each animal. As a result of their findings, the authors recommend products with a small mesh size, < 5 mm^2 (0.2 in.).

Non-biodegradable materials. The use of non-biodegradable products for drainage and slope stability applications may be seen as environmentally unfriendly. Achieving design goals while using degradable or natural materials is preferred. However, when projects have design factors (velocities, shear stresses, loadings, project life, etc.) that exceed what vegetation only or biodegradable products can withstand, geosynthetic, hard armor, and bioengineered (combination of products) design alternatives may be warranted.

Non-biodegradable materials have been found to deter burrowing animals, especially with product types that have a robust material composition with adequate thickness, high tensile strength, and no biodegradable components. This impact may constitute a clear benefit in some settings, such as levee applications, where animal burrows can significantly compromise levee structural integrity. Other methods or materials may not provide the same benefits, even with similar slope stabilization results or other ecological impacts, highlighting the importance of identifying all pertinent performance factors for stabilization projects.

Ecological performance. Any addition of materials to a natural setting has potential to alter habitat quality or quantity, whether or not wildlife and habitat considerations are explicit goals of a stabilization project. Stabilization projects may improve some habitat elements at the expense of others, or have neutral impact. Many slope stabilization methods and materials have explicit environmental benefits (Fischenich and Allen 2000). Methods and materials can be selected to optimize habitat considerations by considering impacts for each type of material or approach on selected habitat elements (Table 4). Note that materials can be combined to increase environmental benefits, such as interplanting of hard armor with vegetation. Elements considered in Table 4 assume methods or materials are appropriate for all other site conditions, and all elements except Riprap and Hard Armor categories assume some vegetative component is included in the application.

Table 4. Generalized environmental impact of selected streambank stabilization measures on aquatic and terrestrial habitat elements compared with bare or eroding streambanks. Note: impacts represent typical applications – actual performance may be enhanced through good design and construction practices.

Ecological Performance Factor	Vegetation Temporary RECP (ECB)	Bioengineering – brush layers, VRSS, log crib	Ordinary / Advanced TRM	HPTRM / ARVS	Riprap	ACB	Hard Armor – gabions concrete, sheet pile
Wildlife access	☺	😐/☺	😐/☺	😐/☺	😐/☹	😐/☹	☹
Aquatic habitat complexity	😐/☺	😐/☺	😐	😐	😐/☺	😐/☹	☹
Riparian / veg. habitat complexity	☺	😐/☺	😐/☺	😐/☺	😐/☹	😐/☹	☹
Shade, temperature	😐/☺	😐/☺	😐	😐	😐/☹	😐/☹	☹
Cover, refugia	😐/☺	😐/☺	😐/☹	😐/☹	😐/☺	😐/☹	😐/☹
Nutrient cycling	☺	☺	😐/☺	😐/☺	☹	☹	☹
Surface-groundwater connection	😐	😐	😐	😐	😐	😐/☹	☹
Water quality – pollutant removal	☺	☺	☺	☺	😐/☹	😐/☹	😐/☹
Water quality – overland sed. capture	☺	☺	😐/☺	😐/☺	😐/☺	😐/☹	😐/☹
Soil development	☺	😐/☺	☺	😐	☹	☹	☹
Construction impacts	😐	😐/☹	😐	😐	😐/☹	☹	☹
Maintenance impacts	😐	😐	😐	😐	😐/☹	😐/☹	😐/☹

☺	Beneficial
😐/☺	Neutral to Beneficial
😐	Neutral
😐/☹	Neutral to Detrimental
☹	Detrimental

Regional/climatic design criteria. Sufficient UV-stability for project design life, appropriate anchoring type, length, and spacing, use of lightweight non-woven fabric to minimize movement of fines, and appropriate choice of vegetation are important to successful TRM applications in any climate. However, some performance factors are setting- or condition-specific (e.g., climate considerations), leading to regional design considerations (Table 5). Generalized conditions and criteria are grouped into six climatic regions to provide region-specific design considerations and keys to region-specific historical product successes, assuming the extreme of expected conditions and site limitations. Specific project site considerations will best guide product and design selection. For example, a HPTRM or an ARVS with minimum strength of 3,000 x 3,000 lb/ft (143.6 x 143.6 kN/m^2) and high UV stability (minimum of 90% strength retained at 5,000 hr) may be required for semi-arid / arid site conditions.

Table 5. Design considerations for TRM materials used in various climate categories, based on observed performance.

Design Considerations	Semi-arid and Desert	Subarctic	Humid and Subtropical	Tropical	Coastal	Mountainous
Intense sunlight / potential for UV degradation	✓	✓	✓	✓	✓	✓
Potential for sparse vegetation establishment	✓	✓			✓	✓
Likelihood of poor soil conditions	✓	✓			✓	✓
Flashy hydrograph[1]	✓					✓
Potential for debris loads	✓		✓	✓	✓	✓
Potential for ice loads		✓				✓
Construction and vehicular loadings	✓	✓	✓	✓	✓	✓
Extreme thermal stress	✓	✓	✓	✓	✓	✓
Extreme thermal stress with humidity			✓	✓	✓	
Freeze/thaw conditions	✓	✓				✓
Wave action			✓[2]	✓[2]	✓	
Potential wildlife entrapment[3]	✓	✓	✓	✓	✓	✓

[1] Flashy hydrographs characterized by rapid increase and decrease in stage can occur anywhere, but are especially prevalent in mountainous watersheds with steep slopes, areas with snowmelt- or rain-on-snow driven high flows, semi-arid and arid regions or areas with rapid urbanization or significant impervious surfaces.
[2] Wave action only in areas with significant water bodies.
[3] Wildlife entrapment potential is especially important for locations with sensitive or endangered species.

PRODUCT SELECTION: Every designer must try to understand all of the specific issues relating to risks that the project may face. Any given project may face one or more external stresses. Some of these stresses are related to human uses (e.g., mowing/maintenance, recreational and construction traffic), setting characteristics (e.g., climate), or an environmental concern (e.g., an endangered species or a nuisance species).

Any one or more of hydraulic, geotechnical, or environmental stress categories or considerations can limit product selection or application (Table 6). A material or specific application might be capable of withstanding certain types of stresses, but not others, so the balance of each set of conditions with materials and installation methods is critical to project success – all criteria must be met by final design. The risk associated with each decision depends on how likely the damage or threat is and how serious the consequence of damage is for project success. For example, an average TRM might carry high probability to experience mowing damage, but if the equipment used is a small lawn mower versus a large utility tractor, or if the material is used in conjunction with a hard armor component, then any damages would either be minimal or not as important to the stability of the project.

Table 6. Flexible channel and slope armoring generalized design and product selection guidelines.

Standard UV Resistance and Tensile Strength Recommendations for Product Classes and Estimated Product Design Life				
Standard Recommendations[1]	**Ordinary TRM**	**Advanced TRM**	**High Performance TRM (HPTRM)**	**Anchor Reinforced Vegetation System (ARVS)**
Estimated Product Design Life	Up to 5 years	Up to 25 years	Up to 50 years	Up to 50 years
Tensile Strength-Minimum Average Roll Values, ASTM D 6818	125 x 125 lb/ft^2 (6 x 6 kN/m^2)	1,500 x 1,500 lb/ft^2 (71.8 x 71.8 kN/m^2)	3,000 x 3,000 lb/ft^2 (143.6 x 143.6 kN/m^2)	3,000 x 3,000 lb/ft^2 (143.6 x 143.6 kN/m^2)
Tensile Strength Retained-All Components, ASTM D 4355	90% at 500 hr	90% at 2,500 hr	90% at 5,000 hr	90% at 5,000 hr
SELECTED HYDRAULIC CONSIDERATIONS				
Selected Performance Considerations	**Ordinary TRM**	**Advanced TRM**	**HPTRM**	**ARVS**
Maximum Permissible Design Velocity[2] **(Vegetated – 70% to 100%)**	≤ 12 ft/s (3.7 m/s)	≤ 16 ft/s (4.9 m/s)	≤ 20 ft/s (6.1 m/s)	≤ 20 ft/s (6.1 m/s)
Maximum Permissible Design Velocity[2] **(Partially Vegetated – 30% to 70%)[3]**	N/A	N/A	≤16 ft/s (4.9 m/s)	≤16 ft/s (4.9 m/s)
Maximum Permissible Design Velocity [2] **(Minimally vegetated – up to 30%)[3]**	N/A	N/A	≤ 12 ft/s (3.7 m/s)	≤ 12 ft/s (3.7 m/s)
Maximum Permissible Design Shear Stress[2] **(Vegetated – 70% to 100%)**	≤ 6 lbs/ft^2 (287 N/m^2)	≤ 10 lbs/ft^2 (0479 N/m^2)	≤ 14 lb/ft^2 (670 N/m^2)	≤ 14 lb/ft^2 (670 N/m^2)
Maximum Permissible Design Shear Stress[2] **(Partially Vegetated – 30% to 70%)[3]**	N/A	N/A	≤ 12 lb/ft^2 (575 N/m^2)	≤ 12 lb/ft^2 (575 N/m^2)
Maximum Permissible Design Shear Stress [2] **(Minimally Vegetated – up to 30%)[3]**	N/A	N/A	≤8 lbs/ft^2	≤8 lbs/ft^2
Permissible Wave Height[5] **(Inland Conditions Only, i.e. Canals & Reservoirs)**	N/A	N/A	≤ 12 in. (30.5 cm)	≤ 12 in. (30.5 cm)
Flow Frequency[4]	Intermittently Loaded	Intermittently Loaded	Intermittently Loaded	Intermittently Loaded & Continuous Flow
SELECTED NON-HYDRAULIC CONSIDERATIONS				
Vehicular Traffic/Mowing Limits	Push Mower	Push Mower	Rubber-tired Vehicles / Rider Mower	Rubber-tired Vehicles / Rider Mower
Vegetation Establishment	Minimum 90% Coverage Required	Minimum 65% Coverage Required	Vegetation Beneficial but Not Required	Vegetation Beneficial but Not Required

Wildlife Entrapment Minimization	Average opening size of 5 mm^2 (maximum)	Average opening size of 5 mm^2 (maximum)	Average opening size of 5 mm^2 (maximum)	Average opening size of 5 mm^2 (maximum)
Applicable Climate Conditions	Temperate	Temperate	Temperate, Semi-Arid, Arid	Temperate, Semi-Arid, Arid
High Loading and/or High Survivability Required	No	No	Yes	Yes
Material Matrix Configuration	Fused monofilaments, Stitch-bonded, Woven	Woven	Woven	Woven + Anchors
Material Composition	Polypropylene, Bio-Degradable, Nylon, Polyester, Recycled, Other Synthetics	Polypropylene	Polypropylene	Polypropylene
GEOTECHNICAL CONSIDERATIONS[6]				
Soil Type	**Site Specific**	**Site Specific**	**Site Specific**	**Site Specific**
Erosion or Failure Mechanism Treatable	Erosion	Erosion	Erosion	Erosion and/or Surficial Slumping
Angle of Repose Can be Exceeded	No	No	No	Yes
Seepage Concerns	No	No	No	Yes

1 All values *minimum average roll value* (MARV), defined as two standard deviations below the mean per ASTM D 4439
2 Reference product-specific product data sheet and apply minimum safety factor of 1.3 to account for short-duration maximum velocity or instantaneous flume testing results that may exceed real world performance (see Figure 6 for duration effects). All values reported less than the maximum value for this reason.
3 Note that additional maintenance may be required during vegetative establishment period. For unvegetated conditions or applications (0%) a non-woven geotetxtile fabric should be considered for use beneath TRM.
4 Non-woven geotextile fabric is recommended beneath ARVS for continuous flow applications and for unvegetated conditions or applications (0%).
5 Wave Action numbers for Inland conditions are based on significant field experience. Wave Action in Non-Inland, coastal or estuarine conditions needs further testing.
6 Site-specific geotechnical considerations including soil type, surficial slumping, global stability, angle of repose, seepage, saturation considerations, etc. must be included as part of the product selection analysis, particularly if a more structural approach may be warranted. An anchored reinforced vegetation solution (ARVS) should be considered where shallow plane sloughing and/or seepage may occur. For areas where global stability is of concern, consult a geotechnical engineer for proper slope evaluation.

Reported maximum permissible parameter standards summarized in Table 6 represent relative industry standards. Specific manufacturers' products may exceed one or more of these values, particularly in HPTRM categories. Design and implementation methods can also increase maximum stresses a project can withstand. For example, an HPTRM anchored with 3-ft earth percussion anchors will withstand greater stresses than the same material fixed in place with staples or short stakes, though this type of information may not be reported in manufacturer specifications for HPTRM materials themselves. Alternatively, a manufacturer might report a maximum permissible velocity that represents results from an unrecognized testing method or a non-standard application that may not be reported as such. Therefore, in addition to referring to manufacturer-reported values, it is important to inquire about testing protocols and testing facility specifications to ensure proper quality assurance and quality control of reported results.

APPLICATIONS/CASE STUDIES: This section presents examples or case studies of various field applications showing vegetated TRMs, HPTRMs, and ARVS field applications in generalized application categories. Field conditions, materials, or other performance factors are briefly described for each project shown. Low tensile strength TRMs are likely acceptable for applications with mild slopes, excellent vegetation establishment potential, and minimal non-hydraulic stresses (e.g., maintenance equipment). High performance products should be considered for all types of slopes if the following conditions exist: (1) construction and maintenance equipment loading, (2) debris and ice loading, (3) utility cuts, (4) hoofed or burrowing animals, (5) connections to hard armor (e.g., bolting to concrete), (6) sparse vegetation establishment potential e.g., (arid/semi arid

conditions), and (7) traffic loading areas (e.g. levees, channels, steep slopes, etc.). An ARVS, which combines earth percussion anchors to HPTRM, should be considered for long or steep slopes, highly unstable channel and/or canal banks, and any time that greater factors of safety are required. This type of solution has shown significant savings when compared to some traditional hard armor and/or retaining wall methods. Geotechnical slope stability analysis must be conducted as part of the design process for sites where an AVRS is considered, and a geotechnical engineer should be consulted throughout.

Mild slopes. Low-strength ordinary TRMs are typically used for mild slopes with minimal non-hydraulic stresses.

Figure 10. Prepared mild slope surface.

Figure 11. TRM installed.

Figure 12. Finished vegetated slope.

Steep (high) slopes. High-strength TRM/HPTRMs should be used on mild and/or steep slopes when conditions for non-hydraulic stresses exist (e.g., mowing, equipment).

Figure 13. Prepared steep slope surface.

Figure 14. HPTRM Installed and hydro-seeded.

Figure 15. Vegetative cover starting to establish.

Ponds/reservoirs. TRMs and HPTRMs have been used on a regular basis for pond and reservoir applications. It is important to note that where rapid drawdown conditions exist in the pond application and/or wave action (up to 12 in.) due to fetch or boating activity exist, a non-woven geotextile fabric should be placed underneath the TRM/HPTRM. The fabric should be placed from the low-water elevation to the normal pooling water elevation and extend above if wave action is expected. This will help resist the migration of fine-grained soil particles through the vegetated TRM/HPTRM. The designer should consider using an advanced or high-performance TRM in these conditions, particularly if slope instability extends below the normal waterline where terrestrial vegetation cannot be used.

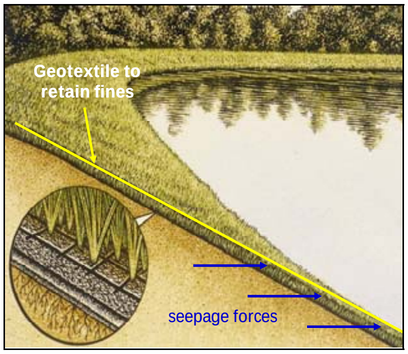


Figure 16. Representative shoreline.

Figure 17. Shoreline installation.

Figure 18. Finished established shoreline.

Channels and drainage swales. TRMs and HPTRMs are regularly used for channel stabilization applications in temperate, arid, and semi/arid conditions. In temperate conditions where vegetative establishment is good (densities of 70% or greater), TRM and HPTRM can be used. Additional design criteria should be considered if the design life of the channel is greater than 5 years and if non-hydraulic stresses will be present (e.g., mowing, construction, debris loadings).

Figure 19. TRM channel application.

Figure 20. TRM-captured sediment.

Figure 21. Fully vegetated TRM.

In arid and semi-arid conditions, the mattings are subject to direct UV degradation with respect to the lack of vegetative density (vegetation ≤ 70%) and significant non-hydraulic stresses are anticipated. In these cases, it is recommended that an HPTRM or ARVS with sufficient UV stability for the project design life be used to resist hydraulic and non-hydraulic stresses.

Figure 22. HPTRM, Arizona (installation).

Figure 23. HPTRM, Arizona (first year).

Figure 24. HPTRM, Arizona (third year).

Canals and streambanks. TRMs and HPTRMs have been used on a regular basis for these types of applications to stabilize stream, canal, and levee slopes adjacent to moving water. An ARVS should be considered if the following conditions exist: continuous flow, steep slopes with potential for shallow plane failure, and toe wave action. If the designer is using this armoring system with expected wave action, a non-woven geotextile should be placed underneath the ARVS System in the wave run-up zone. This will help resist the migration of fine-grained soil particles through the ARVS System. The designer should consider using higher strength materials in these conditions (HPTRMs), or a combination design may also be warranted at the toe of slope consisting of an ARVS armoring system and concrete paving, riprap, gabions, and/or articulated block in the wave zone. If significant debris loadings are anticipated, HPTRM and/or an ARVS Armoring System are recommended.

Figure 25. MSTRM bank installation.

Figure 26. Non-woven geotextile.

Figure 27. Vegetated, established bank.

Figure 28. Canal bank shallow plane failure.

Figure 29. ARVS system installed with anchors.

Figure 30. Finished reinforced vegetated slope.

Levees. ARVS have been used successfully on the land side of earthen levee structures. If the designer is using this armoring system on the water side and/or an area with expected wave action, a non-woven geotextile should be placed underneath the ARVS system in the wave run-up zone. This will help resist the migration of fine-grained soil particles through the HPTRM. The designer should consider using higher strength materials in these conditions, or a combination design may also be warranted on the water side consisting of an ARVS armoring system and concrete paving, riprap, gabions, and/or articulated block in the wave zone. If significant debris loadings are

anticipated, HPTRM and/or an ARVS armoring system are recommended, particularly where instability below normal water level prohibits use of terrestrial vegetation.

Figure 31. AVRS behind sheet piling.

Figure 32. ARVS on earthen levee.

Figure 33. ARVS behind existing I-wall.

Shallow plane failure. ARVS have been used to stabilize shallow plane failures with instability depths of 4 ft or less. The anchor type is a threaded rod (as opposed to a flexible tendon type anchor) and has a maximum load range of 1.5 to 3.0 kips. The TRM must have sufficient tensile strength in these applications, even if a tendon anchor is used, to withstand puncture stresses from and loading of anchors (Baker 2008). These types of applications need to have site-specific designs completed with appropriate anchor depths and spacings. Woven HPTRMs in this application are recommended.

Figure 34. Shallow plane failure.

Figure 35. Anchor layout.

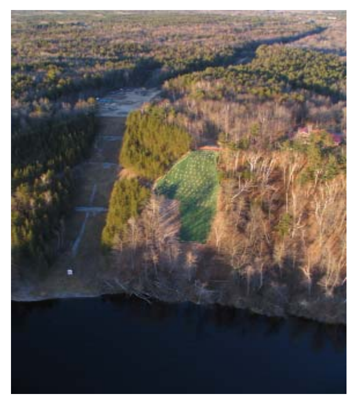


Figure 36. Aerial of finished slope.

Combination design. In a technical note titled “Vegetated Reinforced Soil Slope, Streambank Erosion Control” (Sotir and Fischenich 2003), a vegetated reinforced soil slope (VRSS) soil bioengineering system was defined as “an earthen structure made from living, rootable, live-cut, woody plan material branches, bare root, tubling, or container plant stock in conjunction with rock, geosynthetics, geogrids, and/or geocomposites.” While the emphasis of a permanent vegetated armoring system is the erosion control benefits of the geosynthetic and vegetation components, these are also appropriate components of a VRSS soil bioengineering system for many applications. The use of multiple stability products for a single application has also been referred to as a “combination design” or “hybrid design.” Combinations of TRM/HPTRM/ARVS (soft) and

hard armor products (e.g., riprap, gabion, concrete paving, articulated block) have been used for the project types mentioned above.

Figure 37. ARVS with 9-in. Reno mattress.

Figure 38. Connection of ARVS to mattress.

Figure 39. Finished Installation.

SUMMARY: Flexible channel lining technology changes rapidly and the applications for these materials and methods are expanding. As the industry advances and newer generations of materials are developed and tested, material index properties and performance data should be updated to include new methods and materials, particularly as field applications develop an increased track record.

Sufficient UV resistance and retained tensile strength over time are the essential material performance properties to meet most project design requirements. The following items should be considered during the design, product feasibility, and selection process:

1. Typical TRM, HPTRM, and ARVS applications include:

    - Drainage including ponds, reservoirs, channels, drainage swales, canal and streambanks, stream and wetland restoration, levee protection/stormwater impoundments, overtopping, and overwash protection to landside of levees.
    - Slopes including roadway embankments, wind erosion applications with minimal vegetation establishment, and shallow plane failures.

2. Hydraulic conditions including design velocity, design shear stress, and expected flow duration should be considered when evaluating TRM products. A safety factor (1.3 minimum) should be applied to the manufacturer's published hydraulic flume test data.
3. UV-Resistance per ASTM D-4355 should conform to the following for the specified type of permanent TRM and design life:

    - Ordinary TRM – 90% tensile strength retained at 500 hr for the TRM product to be considered up to a 5-year design life.
    - Advanced TRM – 90% tensile strength retained at 2,500 hr for the TRM product to be considered up to a 25-year design life.
    - High-performance TRM – 90% tensile strength retained at 5,000 hr for the TRM product to be considered up to a 50-year design life.
    - Anchor reinforced vegetation system (ARVS) – 90% tensile strength retained at 5,000 hr for the TRM product to be considered up to a 50-year design life. (Projects that

may have 100% expected vegetation establishment coverage need not necessarily be designed to that assumption.)

4. High tensile strength products should be considered where stresses include construction and maintenance equipment loading, debris and ice loading, utility cuts, hoofed or burrowing animals, connections to hard armor (e.g. bolting to concrete), sparse vegetation establishment potential, and traffic loading areas (e.g. levees, channels, steep slopes, etc.). Tensile strength per ASTM D-6818 is suggested to conform to specific tensile strength ranges for specified types of TRM (see Table 3).
5. Flexibility of a TRM per ASTM D6575 is an important predictor of how well the TRM will stay in direct contact with the surface subgrade; direct contact between the TRM and subgrade is crucial for (1) vegetation establishment, and (2) preventing the potential for erosion between the TRM and subgrade.
6. A maximum TRM opening size of 5 mm^2 (0.2 in.) should be used in sensitive wildlife habitat locations to prevent wildlife entrapment.
7. ARVS (HPTRM with specialized tie-down anchors) may be required for applications that include the following: (1) hydraulic conditions that approach design limitations (i.e. velocity, shear stress, and flow duration), (2) opportunity for use of maintenance vehicles, (3) sandy soils, (4) sparse vegetation potential, (5) desire for minimal long-term maintenance, and (6) desire for higher safety factors.
8. TRM project design should include appropriate tie-down type, length, and frequency/spacing.
9. Installation is key to the success of TRM product performance. Crucial installation factors include (1) appropriate connections and trenching at the boundary conditions, and (2) direct contact between the TRM and surface subgrade (tie-down and soil fill) is ensured by matching grading and conditions to product flexibility.
10. The industry should be encouraged to continue to improve product performance and design guidelines to include improved consistency in published MARV values and ASTM testing (see Table 6). Additional published test values beyond standard strength parameters should include aging statistics for more definitive prediction of field performance, more widely published UV testing beyond 1,000 hr, and published average and maximum TRM opening sizes to meet environmental considerations.
11. Product-specific field case studies should continue to be added to the published body of work for flexible channel lining materials performance for a variety of all types and specific applications to augment short-duration controlled parameter laboratory testing.

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